

Spray Combustion Cross-Cut Engine Research

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Sponsor: DOE Vehicle Technologies Program
Program Managers: Gurpreet Singh and Leo Breton

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Overview

Timeline

- Project provides fundamental research that supports DOE/industry advanced engine development projects.
- Project directions and continuation are evaluated annually.

Budget

- Project funded by DOE/VT:
FY15 - \$900K
FY16 - \$1030K

Barriers

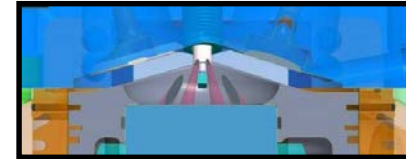
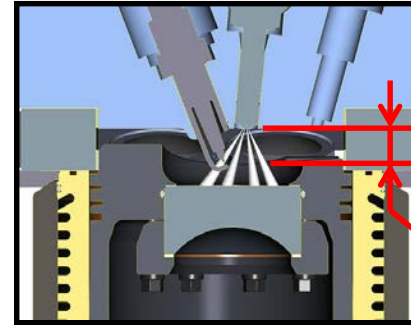
- Engine efficiency and emissions
- Understanding direct-injection sprays
- CFD model improvement for engine design/optimization

Partners

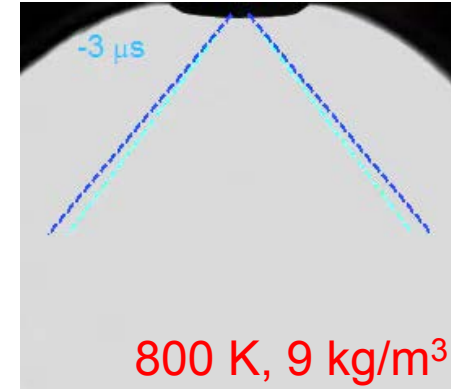
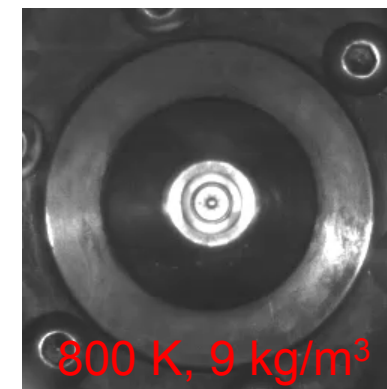
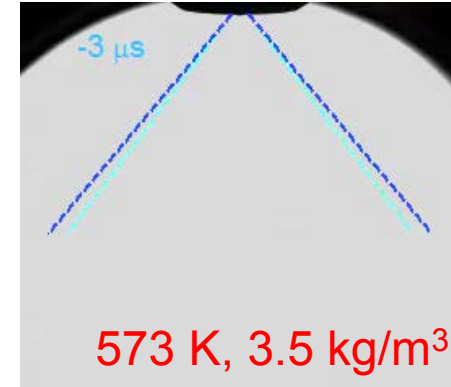
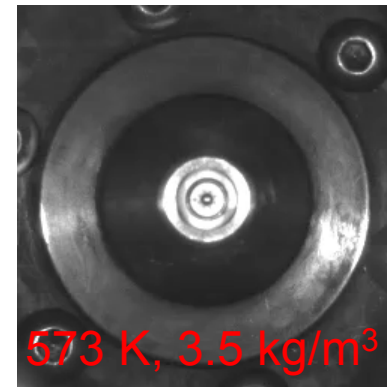
- 15 Industry partners in MOU: Advanced Engine Combustion
- Engine Combustion Network
 - >20 experimental + >20 modeling
 - >100 participants attend ECN4
- Project lead: Sandia
 - Lyle Pickett (PI), Scott Skeen

Engine efficiency gains require fuel (DI spray) delivery optimization

- Barriers for high-efficiency gasoline
 - Engine knock
 - Slow burn rate or partial burn
 - Particulate emissions
 - Heat release control when using compression ignition
 - Lack of predictive CFD tools
- Influence of direct-injection spray
 - Affects temperature non-uniformities
 - Mixture/flow preparation near spark
 - Fuel films on piston/injector, rich pockets
 - Intentional control of stratification/residence time to stage heat release
 - Identified as a high priority for CFD



8-hole, gasoline
80° total angle
~15mm



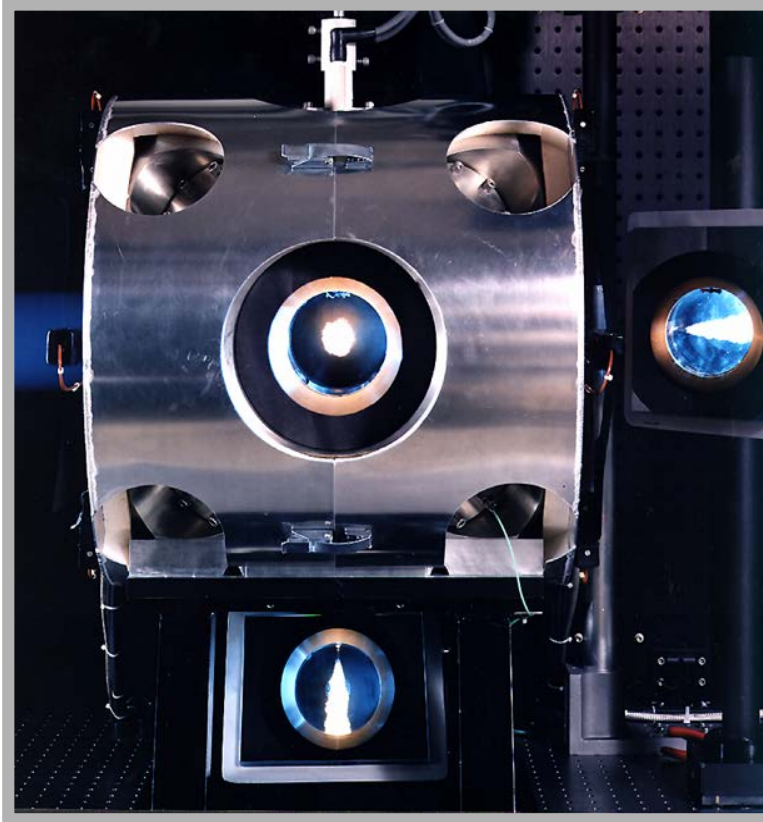


Project Objectives – Relevance

Major objective: experimentation at engine-relevant spray conditions, allowing development of predictive computational tools used by industry

- Provide fundamental understanding to make transient gasoline and diesel spray mixing and velocity predictive
 - Predictive combustion must be preceded by predictive mixing—still a weak link
 - Plume-plume interactions and aerodynamics leading to spray collapse
 - Perform PIV using unique high-speed capabilities
 - Develop understanding of internal flow effects
 - Focus on targets for with significant CFD activity as part of the Engine Combustion Network
- Provide a link between spray mixing and combustion
 - Characterize vaporization, ignition, soot formation processes
 - Models are deficient in these areas with serious consequences on emissions and efficiency

Experimental approach utilizes well-controlled conditions in constant-volume chamber



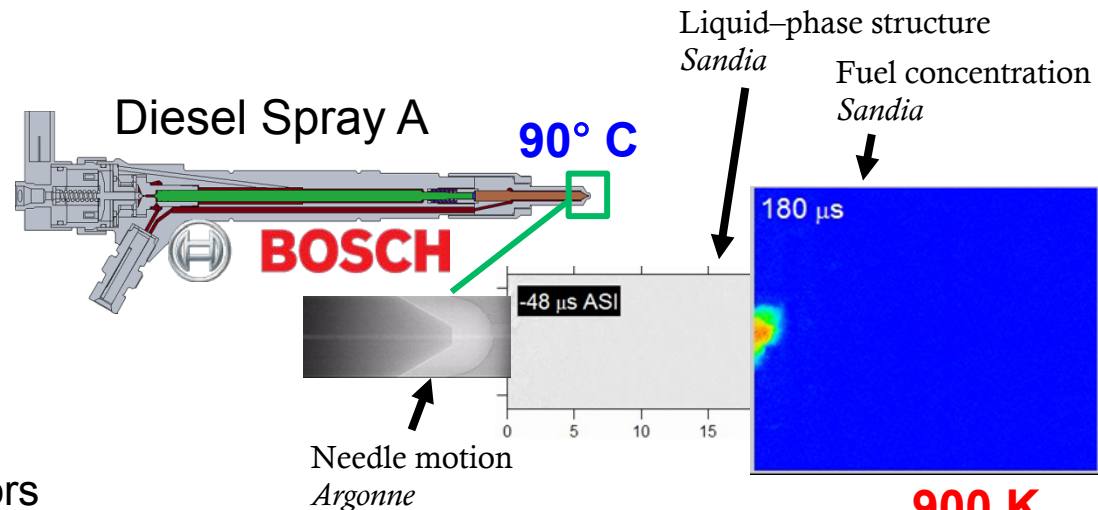
- Well-defined ambient conditions:
 - 300 to 1300 K
 - up to 350 bar
 - 0-21% O₂ (EGR)
- Injector
 - single- or multi-hole injectors
 - diesel or gasoline (cross-cut)
- Full optical access
 - 100 mm on a side
- Boundary condition control needed for CFD model development and validation
 - Better control than an engine
 - Easier to grid

How does this experimental data impact computational tools used by industry?

Collaborative research through the Engine Combustion Network accelerates CFD model development

Approach

- Develop diesel and gasoline target conditions with emphasis on CFD modeling shortcomings
- Comprehensive experimental and modeling contributions
- Diesel Spray A, B, C, D
- Gasoline Spray G
- Engine datasets using these injectors are now available

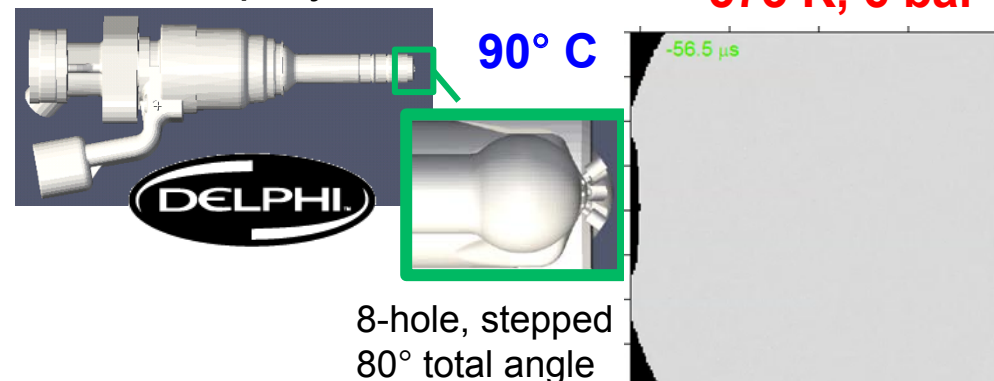


>60 measurements/diagnostics contributed from >15 institutions

ECN workshop organization

- Organizers gather experimental and modeling data, perform analysis, understand differences, provide expert review, in 10 different topics
- Monthly web meetings
- In-person workshop
 - ECN4 September 2015
 - ECN5 April 2017

Gasoline Spray G





Approach - Milestones

- ✓ **Aug 2015**

High-speed velocity measurements of Spray G and Spray A

- ✓ **October 2015**

Characterize the plume-plume interaction of gasoline Spray G at various operating conditions, in light of internal geometry measurements

- ✓ **Nov 2015**

Develop rig for internal nozzle flow characterization

- ✓ **December 2015**

Perform quantitative soot measurements over a range of operating conditions using improved extinction imaging setup

- ✓ **March 2016**

Compare spray and combustion behavior of diesel Spray C (cavitation) and Spray D

- **May 2016**

Characterize chamber turbulence/velocity boundary conditions as an input for CFD

- **July 2016**

Perform high-speed imaging diagnostics to establish ignition and lift-off mechanisms

- **August 2016**

High-speed planar mixing measurements

- **September 2016**

Investigate effect of fuel type at “supercritical” conditions

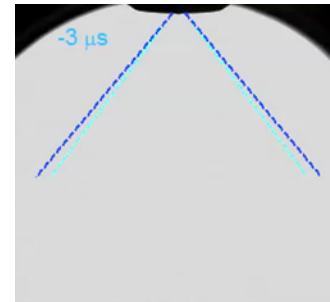
What causes GDI plume redirection/collapse?

- ECN research shows Spray G plume angle does not match drill angle
- Plumes attracted to jet centerline
- 8 plumes collapse into one merged jet near the end of injection
- Research examples showing these effects from ECN4:

- Internal flow modeling shows plumes diverging from drill angle inside nozzle (Argonne, Delphi, PoliMi, UMass/GM)
- Radiography and tomography for non-vaporizing fuel concentration from 2 to 10 mm (Argonne)
- Phase-doppler interferometry for droplet size and velocity at 15 mm (GM)
- Gas-phase mixing by planar LIF after the end of injection (IFPEN)
- Line-of-sight diagnostics indicate earlier/later collapse at different operating conditions (flash boiling, BDC injection conditions)

side-view liquid extinction imaging

Injector #28



Ambient Gas

573 K

6 bar

0% O₂

Fuel

363 K

200 bar

iso-octane

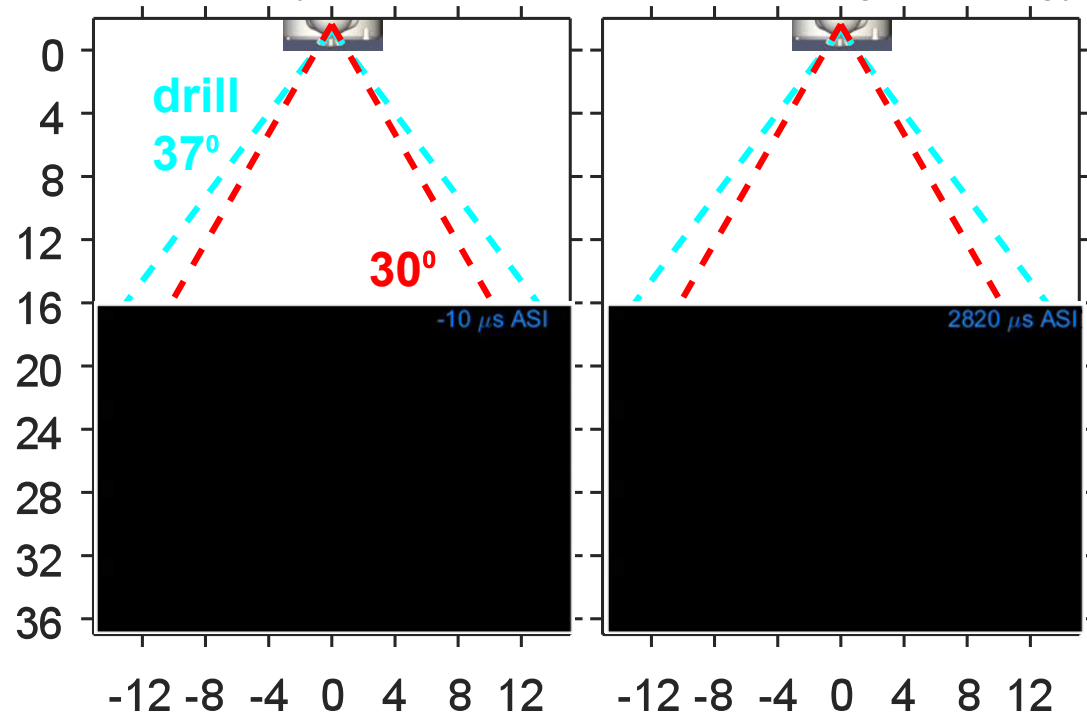
170 μm nozzle

0.8 ms injection

100 kHz Planar Imaging

early period

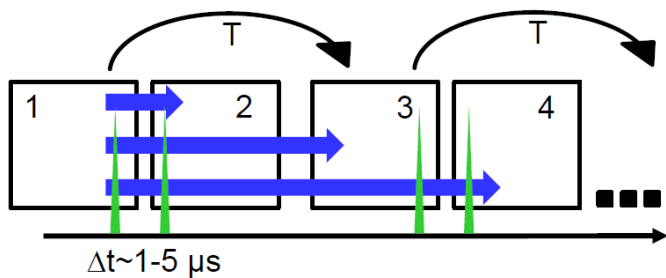
late period (higher energy)



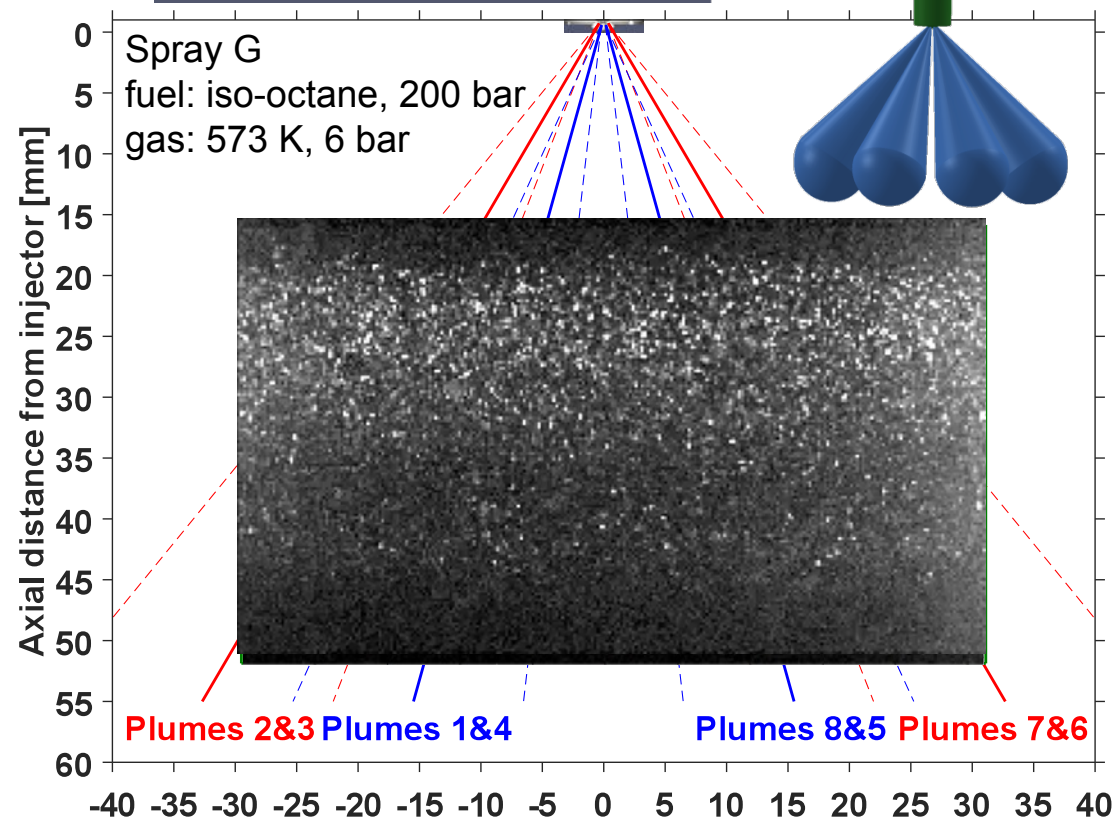
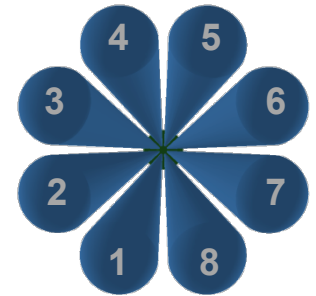
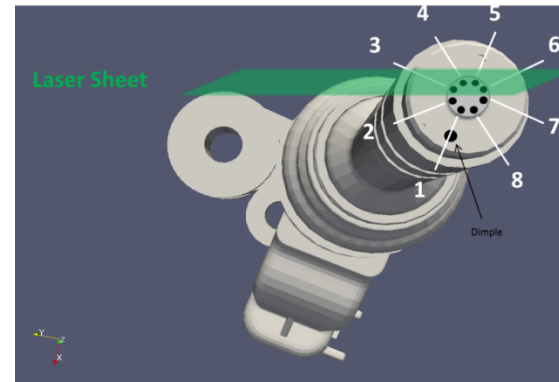


Unique high-speed velocity diagnostic applied

- Custom pulse-burst laser system developed
 - 100 kHz pulse pairs
 - 500 pulse pairs (5 ms burst)
 - 15 mJ/pulse at 532 nm
 - Funded by internal Sandia project (PI J. Frank)



- Applied PIV
 - 1 μm zirconia seed in gas phase
 - 200 kHz imaging on high-speed CMOS camera
 - Liquid-phase avoided by probing between plumes and moving downstream



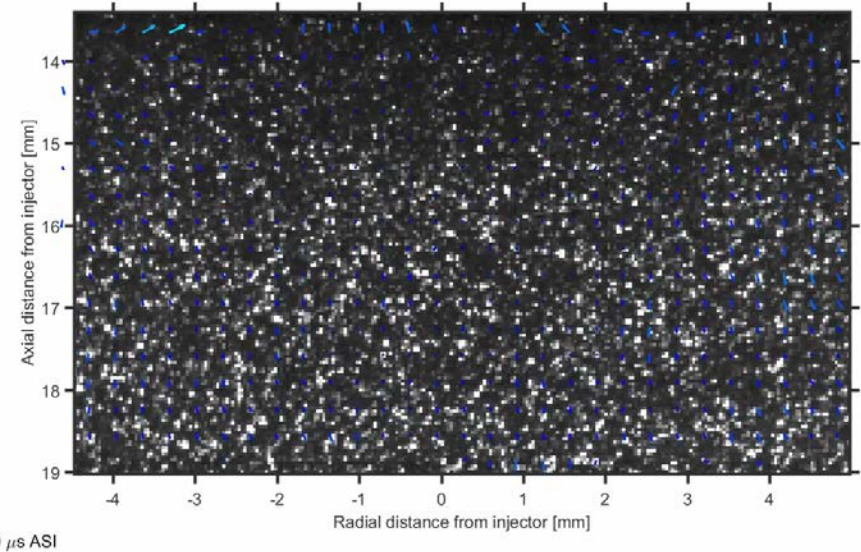
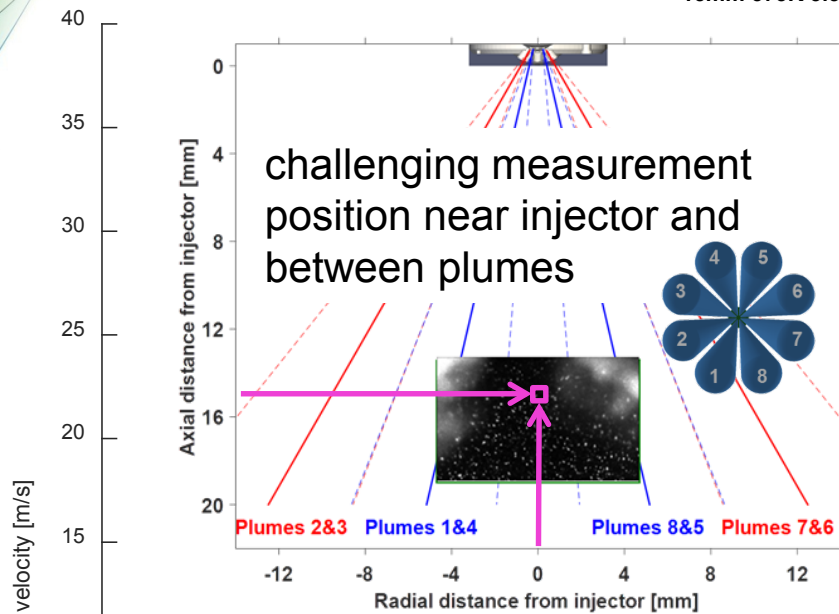


Time evolution of velocity between plumes

15mm 573K 3.5kg/m

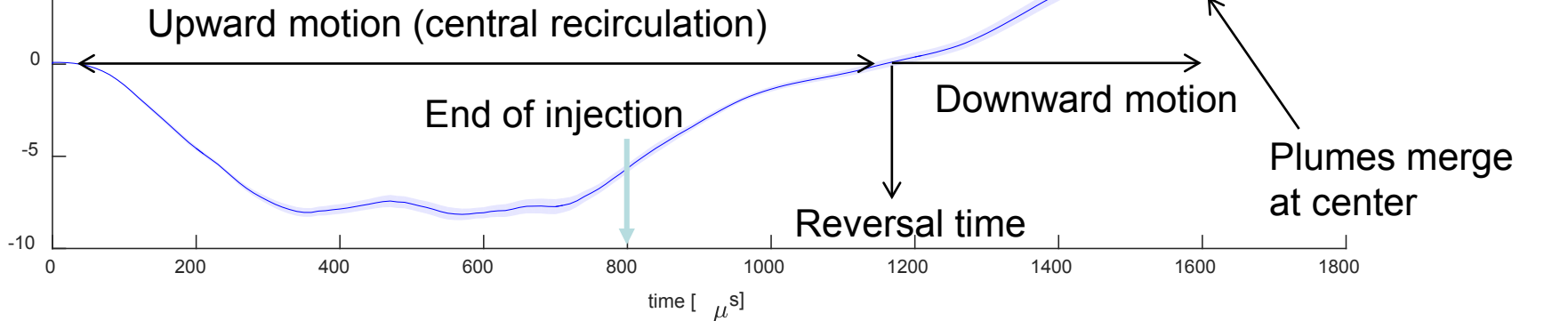
3

processed velocity using
sliding sum of correlations



Processing performed by Panos Sphicas, visitor from Imperial College London

ensemble-average axial velocity

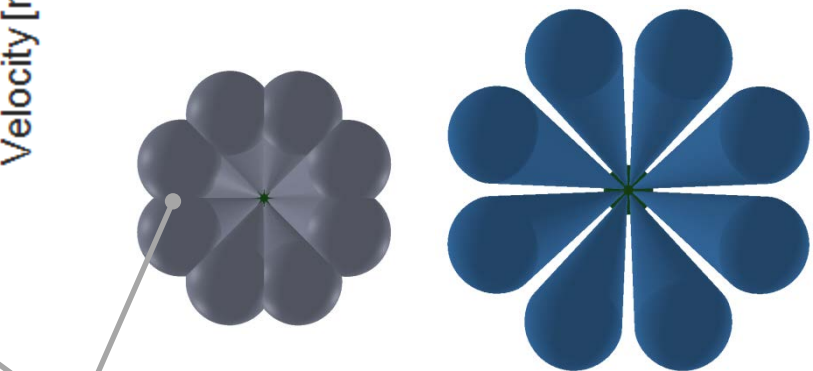
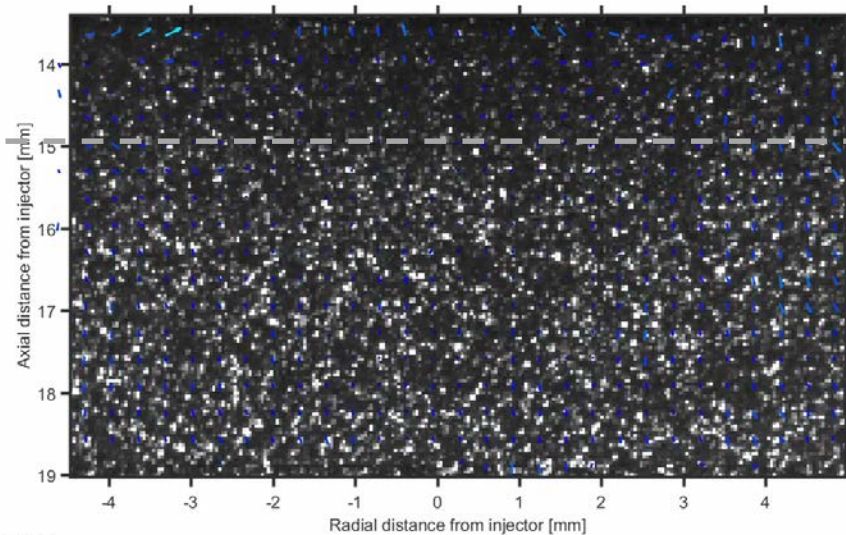
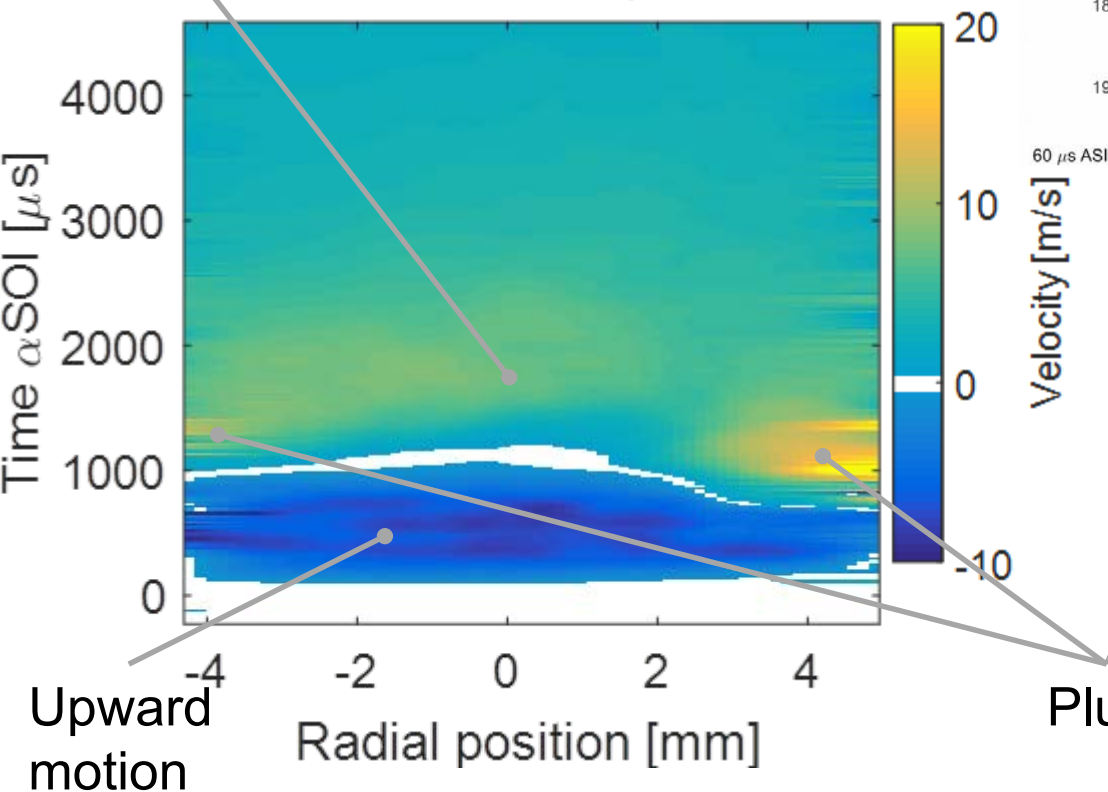




Time evolution of velocity between plumes

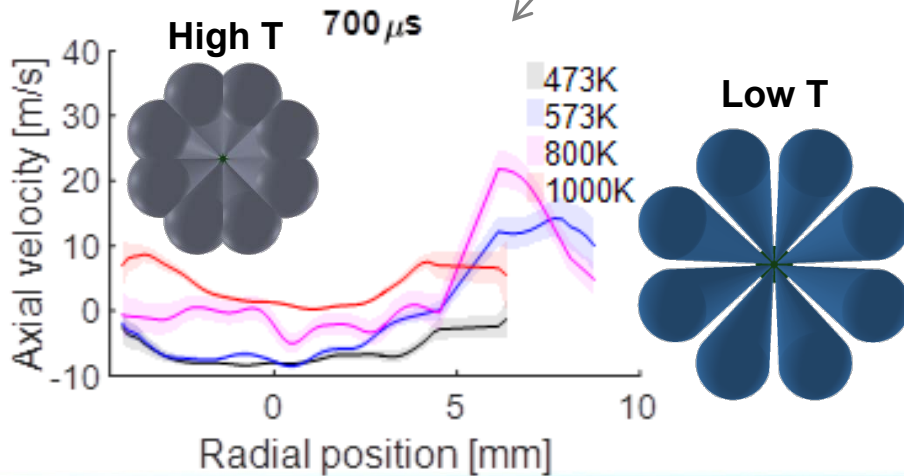
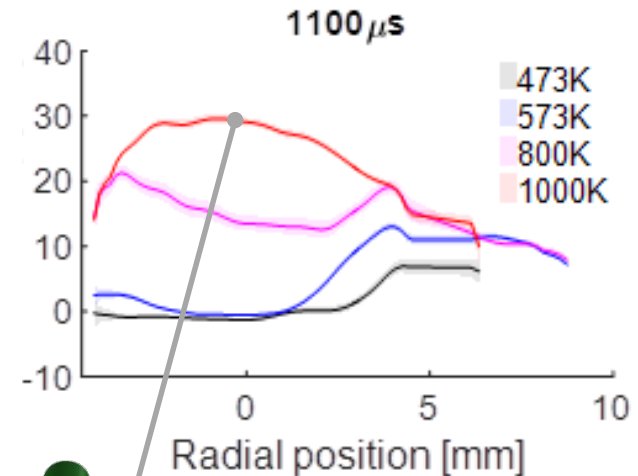
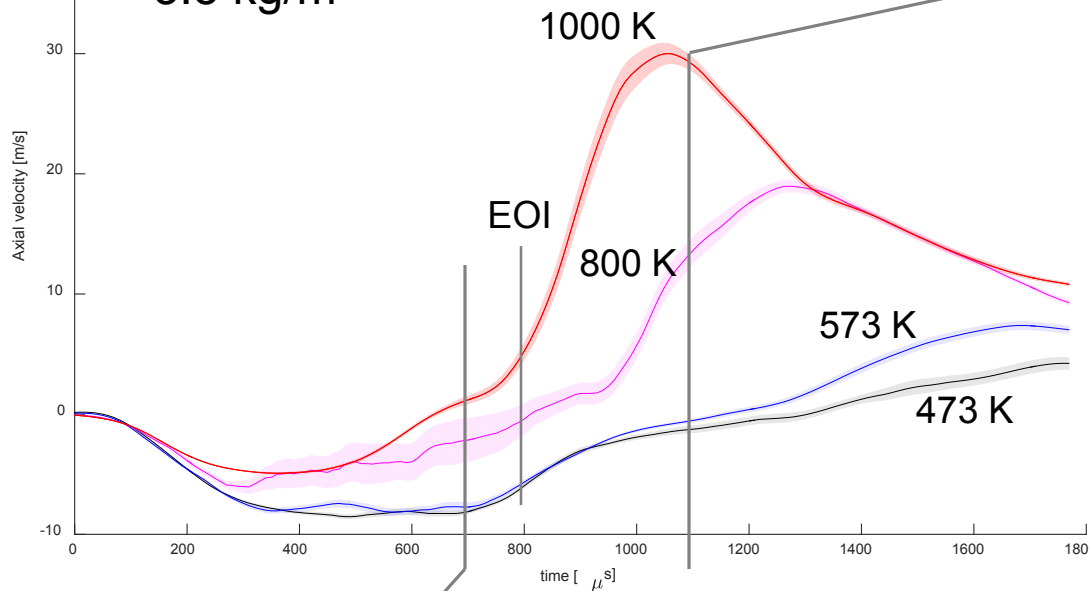
All plumes merge
at center

15 mm axial position



Ambient temperature changes plume interaction

15 mm axial, centerline
3.5 kg/m³

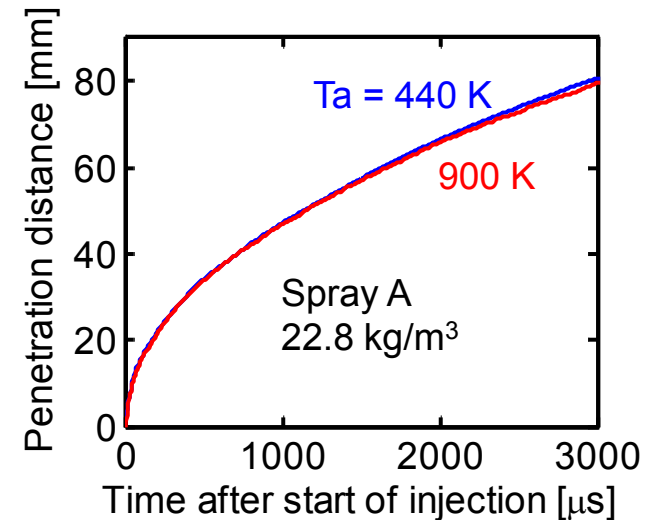
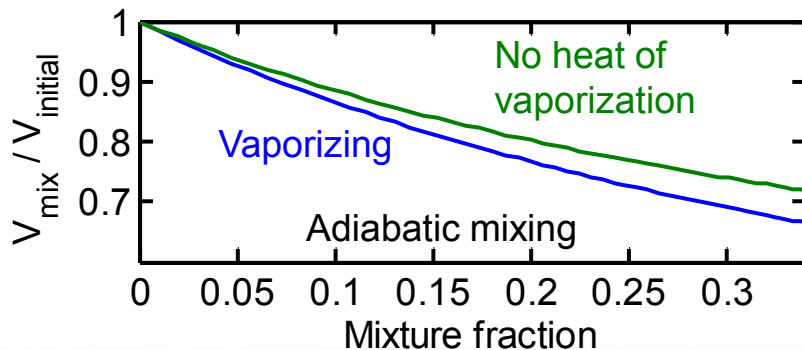


- Plume interaction modified by increasing ambient temperature
 - lower central recirculation velocities
 - faster merging of plumes
 - plume direction towards centerline
- Late-stage fuel delivery is entirely different
 - Fast-moving central plume at higher temperatures

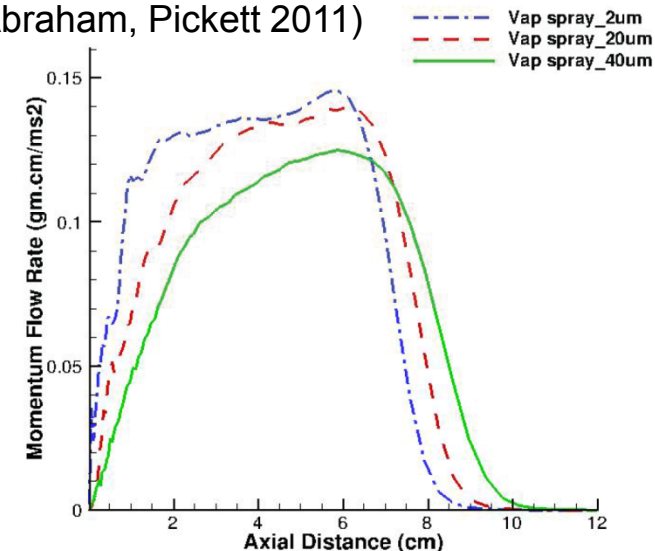
Technical Accomplishments

Why does gas temperature modify spray aerodynamics?

- In isolated jets, penetration mainly depends upon ambient density, not temperature.
 - Greater differences at low ambient density.
- With enhanced vaporization, fuel/gas momentum exchange is expected to be more complete
- Contraction by vaporization and mixing with cold high molecular weight fuel allows more mass “storage” within plumes (having the same cone angle)
- Effects combine to create more immediate plume interaction at higher temperature
- Our velocity measurements also indicate
 - early plume interaction with higher ambient density
 - dependency upon injection duration
 - faster interaction at target T (573 K) compared to room T



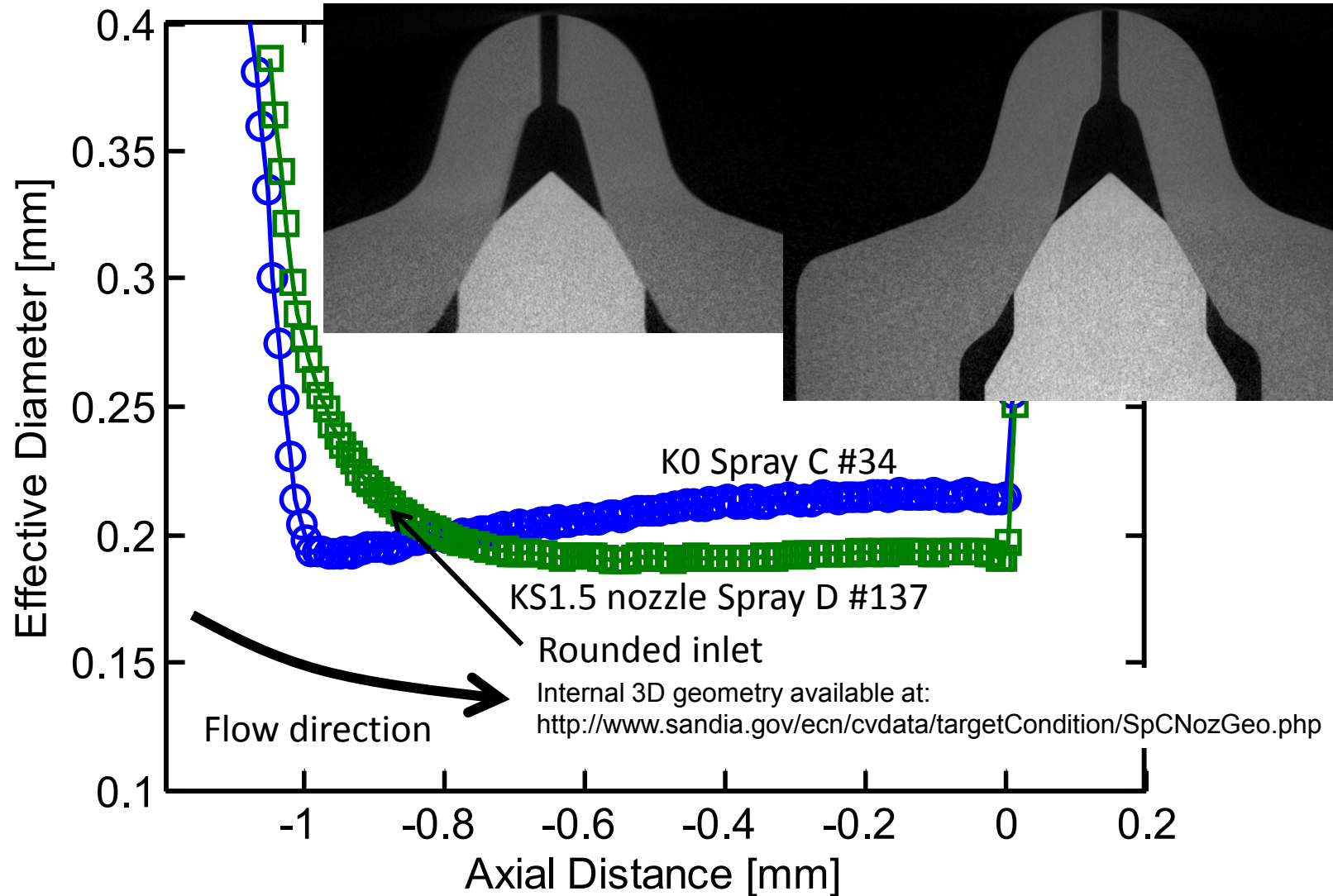
Momentum flow rate of entrained ambient gas (Bajaj, Abraham, Pickett 2011)



Nozzle inlet shape effect on spray development and combustion investigated

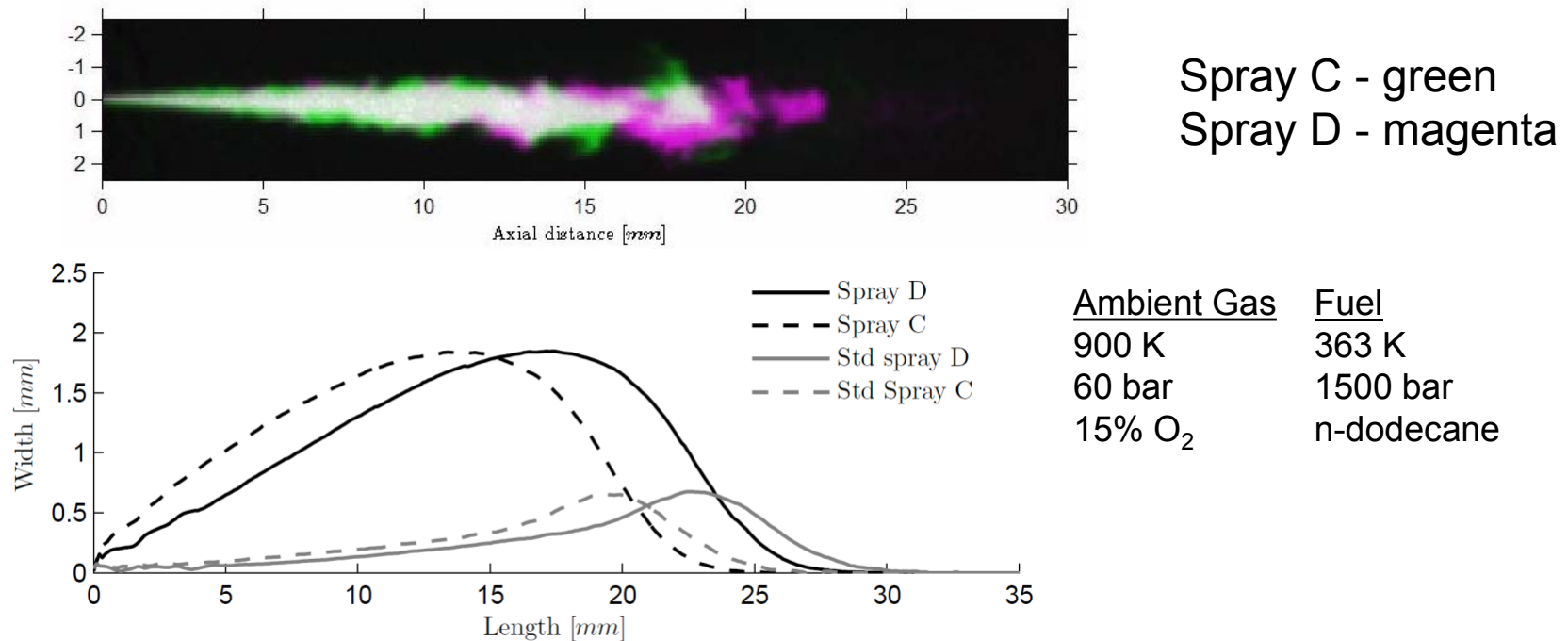
ECN Spray C #34

ECN Spray D #137



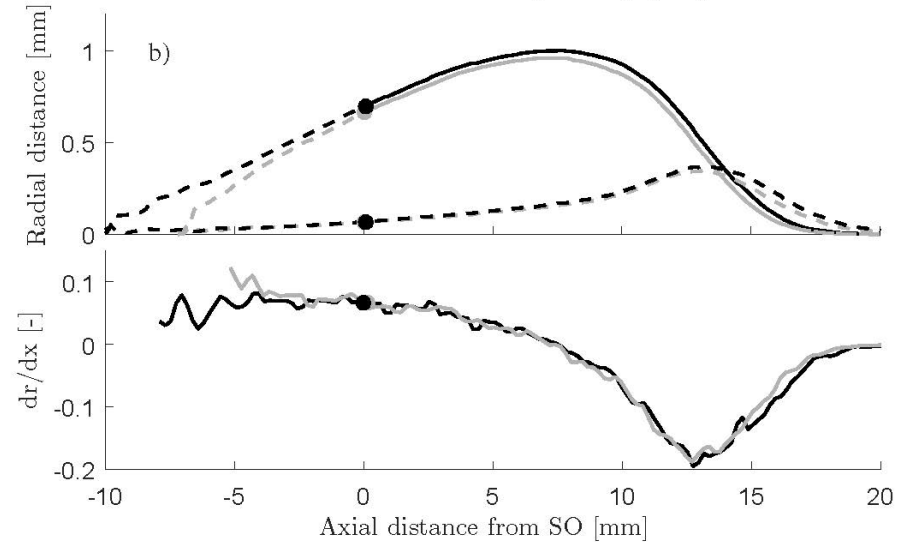
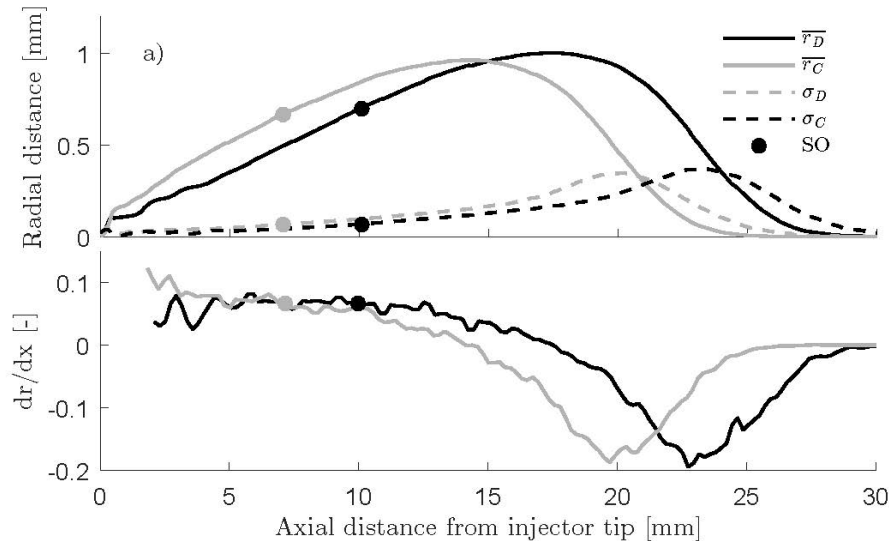


Comparison of liquid penetration and evaporation

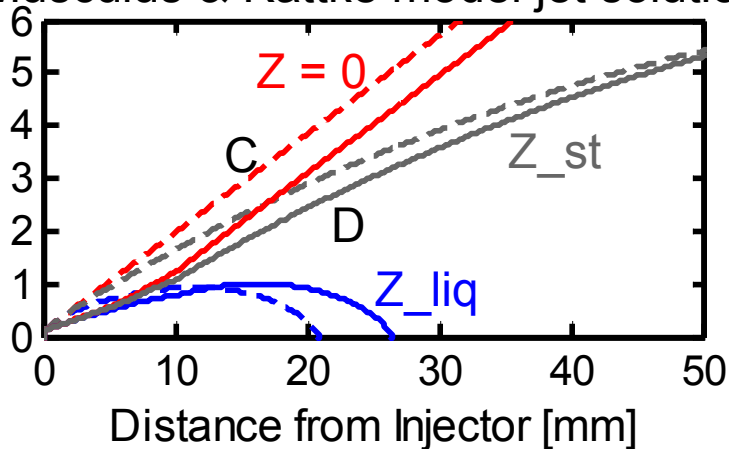


- Liquid/vapor boundary is wider and more deformed closer to the nozzle for Spray C
- Width of spray correlates with magnitude of variance at the boundary

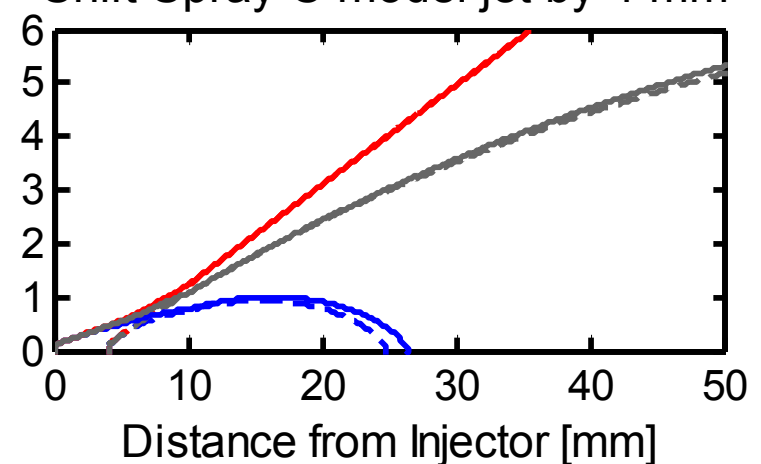
Liquid distributions show remarkable similarity, when referenced to different offset distances



Musculus & Kattke model jet solution

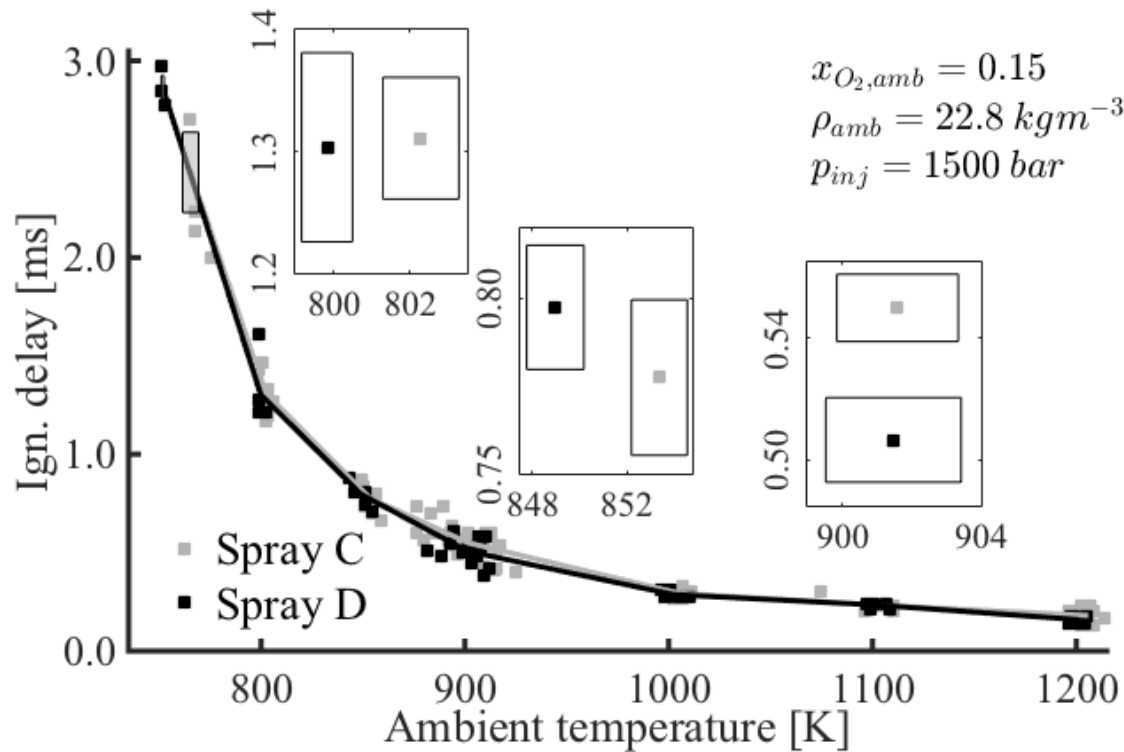


Shift Spray C model jet by 4 mm

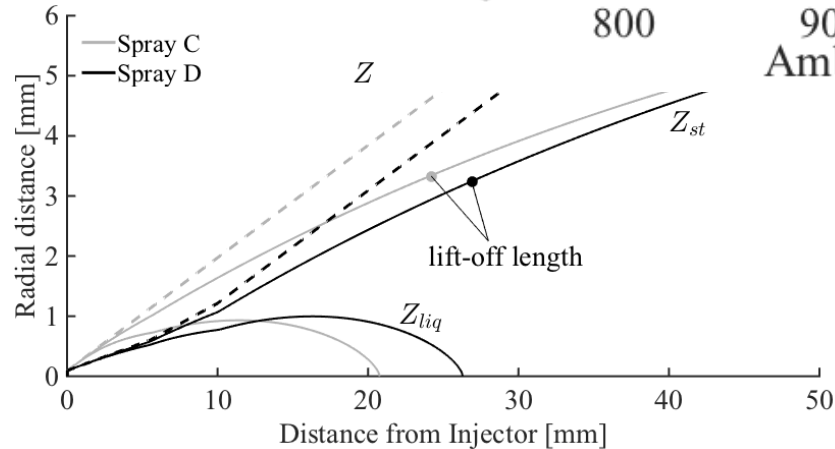
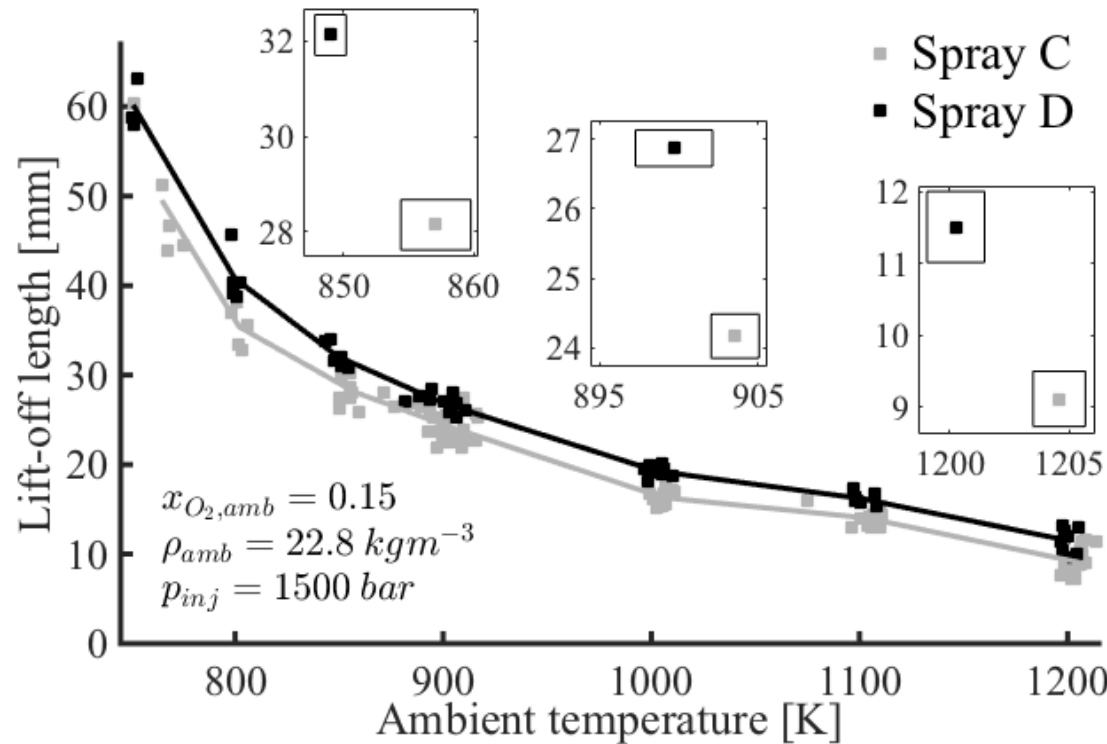


Technical Accomplishments

Very little difference in ignition delay for Spray C and Spray D



But a several mm offset in lift-off length persists over a wide parameter space



- Wider near-field spray ultimately produces shorter lift-off length
- Substantial difference!
- Considering combustion chamber and jet-jet interactions

Other major accomplishments

- Detailed soot measurements and analysis over a wide range of diesel operating conditions, with careful analysis from multiple CFD soot modeling teams
 - Review paper (SAE 2016-01-0734) and ECN4 topic involving 11 institutions
 - Affecting 5 different CFD packages used by industry
- Mixing and cool flame measurements demonstrate the importance of mixing leading to ignition in rich mixtures
 - Presentation accepted for Proc. Combustion Institute 2016
- Characterized gasoline Spray G using long-distance microscopy and using multiple injections at other operating conditions
 - Detail affecting “dribble”, films, and poorly mixed fuel leading to PM
 - Significant analysis of geometry using optical microscopy and x-ray tomography
- Showed how transients in spray spreading angle change ignition and combustion position (SAE 2015-01-1828)
- Compared Spray B combustion results in spray chamber compared to engine
 - Collaboration with Sandia (Musculus), IFPEN, Ist. Motori, Poli. Milano
- Leading the Engine Combustion Network activity
 - Supervised major topics in gasoline sprays and diesel soot formation at ECN4
 - Revamped ECN website and data archive
- Transparent nozzle rig completed and operating



Close collaboration and pathway to better CFD tools

Experiment

Sandia	Mich. Tech.
Argonne	Meiji
IFPEN	Infineum
CMT	Chalmers
CAT	KAIST
GM	Aachen
Delphi	Melbourne
Bosch	Brighton
TU/e	Michigan
Ist. Motori	

CFD codes used

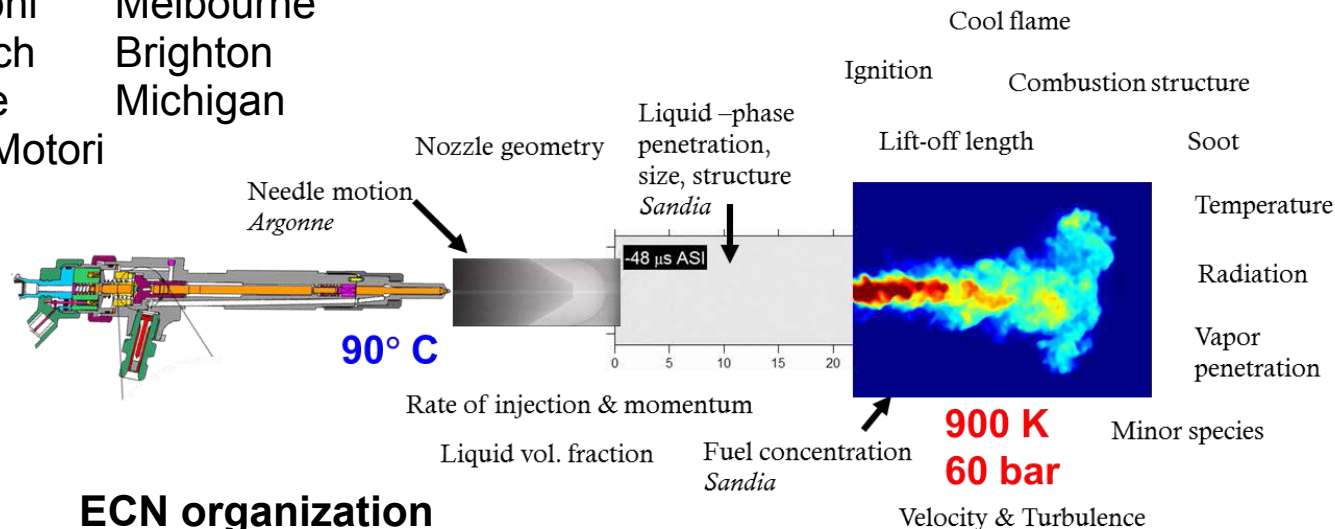
CONVERGE
Star CD
Open FOAM
KIVA
ANSYS Fluent & CFX
FORTE
RAPTOR
other research codes...

CFD approaches

RANS
LES
High-fidelity LES
Eulerian-Eulerian
Eulerian-Lagrangian
Dense fluid
many spray and combustion variants...

Modeling submissions

Sandia
Argonne
IFPEN
CMT
PoliMi
UMass
UNSW
Penn St.
TU/e
UW-Madison
Purdue
ETH-Zurich
Aalto
Aachen
DTU
Cambridge
Georgia Tech
Chalmers
GM...



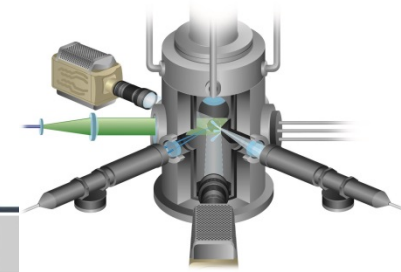
ECN organization

- Monthly web meetings
- Workshop organizers gather experimental and modeling data, perform analysis, understand differences, provide expert review
- Very tight coordination because of target conditions

Most industry use ECN data to test their CFD practices

Future work

- Facilitate model improvements for Spray G gasoline dataset (FY15-FY16)
 - Argonne (Converge) and PoliMilano (OpenFOAM) have agreed to compare RANS and LES predictions to our velocity and mixing datasets
 - Expand high-speed PIV dataset to other positions and operating conditions
 - Specifically focus on phenomena that affects particulate formation
- Diesel research activities (FY17)
 - Investigate the (miscible) structure of fuel sprays with fuel blends and realistic diesel fuel, including the use of cavitating fuel injectors
 - Perform high-speed planar imaging of ignition and mixing (using custom 100 kHz pulse burst laser)
 - Quantify soot formation for Spray C (cavitating) and Spray D injectors
 - Compare cavitating and non-cavitating nozzles
- Expanding to a new high-throughput laboratory (funded via Co-Optima) will improve the efficiency of this research
 - Heated chamber allows 300x speedup
 - Model validation datasets will have lower uncertainty





Responses to previous year reviewer comments

- On the value of quantitative spray datasets that affect CFD modeling tools:
 - “Engine Collaboration Network (ECN) is a brilliant concept which is a true, non-competitive collaboration that brings together national labs, universities, component suppliers, and engine makers. The ECN multiplies the investment that DOE puts into it many fold.”
 - “the amount of progress made on Spray G and gasoline sprays was disappointing”
 - Response: Our charter is to work on both gasoline and diesel, but with limited time, the FY2015 presentation included more diesel work. Our gasoline velocity datasets developed this FY address serious shortcomings in current CFD practices. We do not have the capacity to characterize every type of injector, so we focus on measurements that enable predictive CFD generally (ECN method). We are excited for our experimental capacity to expand significantly (300x) with the addition of a high-throughput spray chamber.
- Research prioritization for spray mixing and combustion:
 - “multi-plume effects should be considered in addition to single-plume experiments”
 - “spray details and ECN work needs to be directly relatable to high efficiency engines”
 - “work is not relevant enough to LD fleet unless more gasoline work is performed”
 - Response: Our work with multi-plume Spray G addresses serious barriers affecting SI engine efficiency. Unpredictable changes in plume interactions that change mixing will affect knock, particulate matter, COV—all of which affect efficiency. In addition, we plan to specifically target GDI injection conditions for high-efficiency gasoline compression ignition.



Presentation Summary

- Project is relevant to the development of high-efficiency, low-emission engines, which all use direct-injection sprays
 - Observations in controlled environment lead to improved understanding/models for engine development
 - We address specific challenges facing current injection systems as well as future concepts
- FY16 approach addresses deficiencies in spray combustion modeling
 - Unique high-speed velocity dataset provided to address sources of plume-to-plume interaction and collapse
 - Internal nozzle flow effects on spray dispersion with links to combustion
- Collaboration through the ECN expanded to accelerate research and provide a pathway for improved CFD tools used by industry
- Future plans will continue research in gasoline and diesel sprays using unique tools and facilities



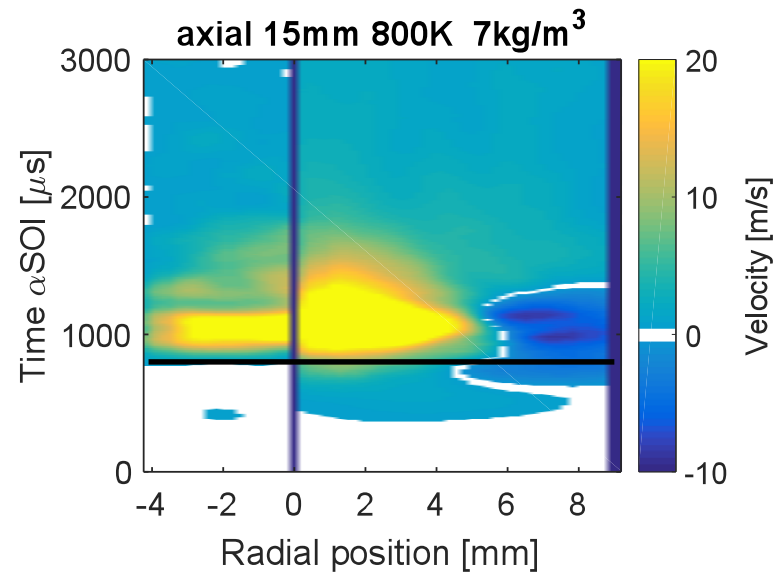
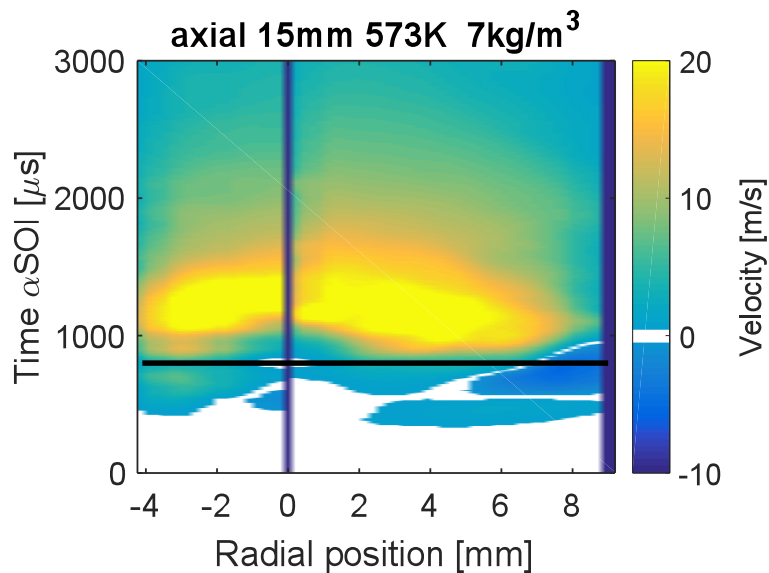
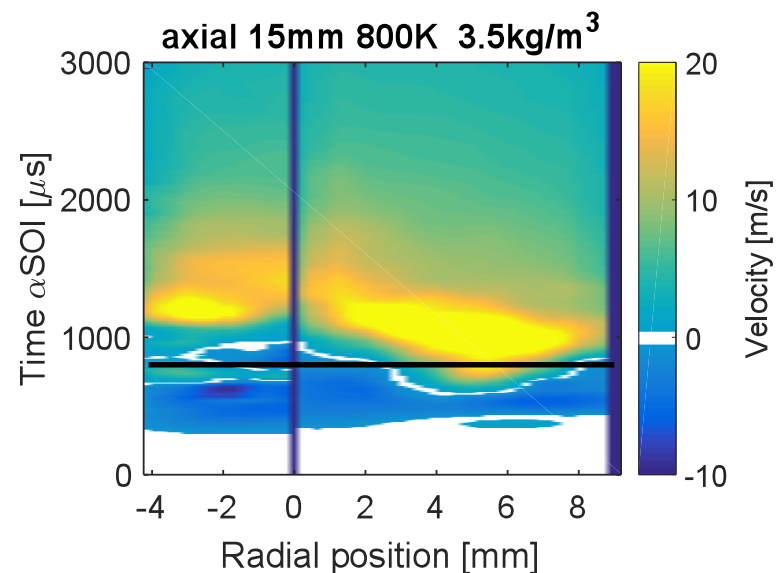
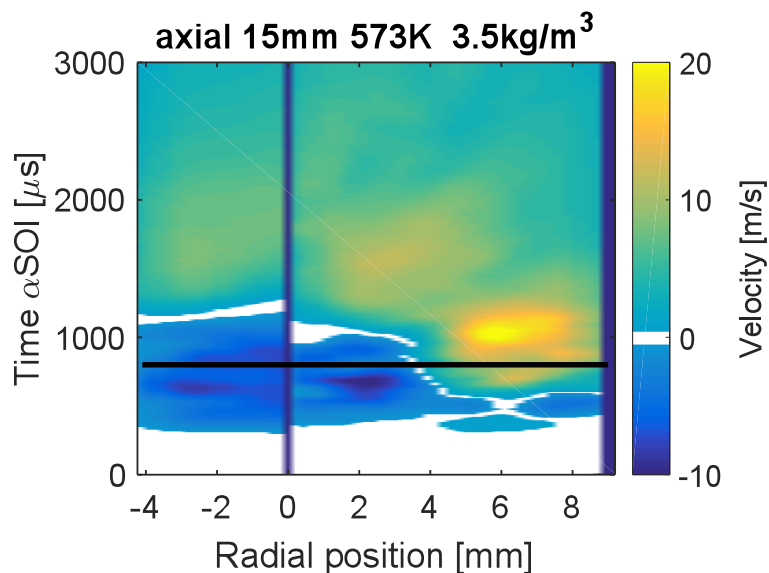
Acknowledging FY16 staff and visitors performing spray combustion research at Sandia

- Scott Skeen, Sandia National Laboratories
- Jonathan Frank, Sandia National Laboratories
- Julien Manin, Sandia National Laboratories
- Adam Ruggles, Sandia National Laboratories
- Panos Sphicas, Imperial College London
- Koji Yasutomi, Hino Motors
- Yongjin Jung, Korean Adv. Inst. of Science and Technology (KAIST)
- Fredrik Westlye, Technical Univ. of Denmark

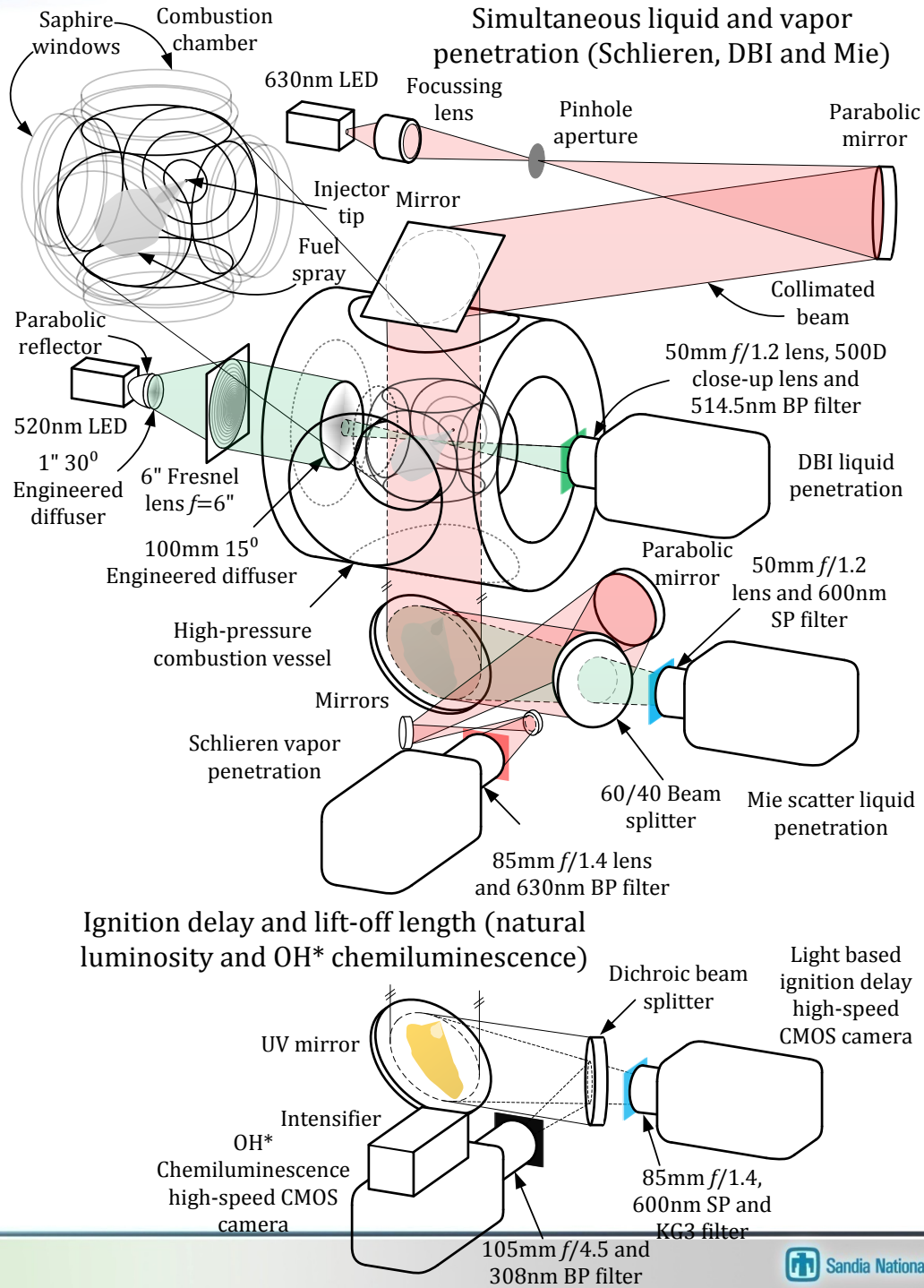


Technical Backup Slides

Velocity maps at different operating conditions



Experimental setup: Spray C and D



Comparison of C and D nozzle flow rates

- Specification called for larger cylindrical (K0) nozzle diameter for Spray C to account for smaller flow coefficients and match flow rate of Spray D
 - But actual minimum diameter was only slightly larger
- Mass and momentum flow rate measurements (provided by CMT, Valencia, Spain) confirm lower flow rates, lower flow coefficients
 - Effective nozzle diameter is smaller for Spray C compared to Spray D
 - This issue addressed during analysis of results

	(Spray D)	(Spray C)
Serial number	209134D	210037C
$D_{nominal}$ [μm] (specified)	186	200
D_{min} [μm] (measured)	186	187
D_{in} [μm] (measured)	193	188
D_{out} [μm] (measured)	186	208
K-factor [-] (specified)	1.5	0
K-factor [-] (measured)	0.55	-2.3
Nozzle shaping/hydroerosion	to $C_d = 0.86$	5%
\dot{m} [g/s] (150 – 6 MPa)	11.96	10.12
\dot{M} [N] (150 – 6 MPa)	7.13	5.83
C_D [-] Discharge coefficient. $C_D = \frac{\dot{m}}{\pi/4 D_{min}^2 \sqrt{2\rho_f \Delta P}}$, where $\rho_f = 717.9 \text{ kg/m}^3$ @70°C and $\Delta P = 144 \text{ MPa}$	0.97	0.81
Area-contraction coefficient $C_a =$ * $C_a > 1$ is not physical but is most likely reflective of experimental uncertainties to derive its value	1.03*	0.89

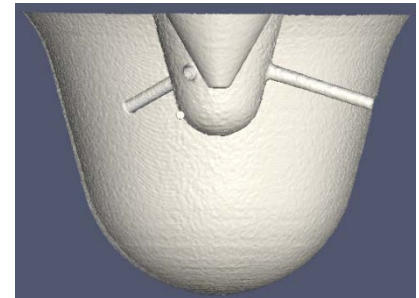
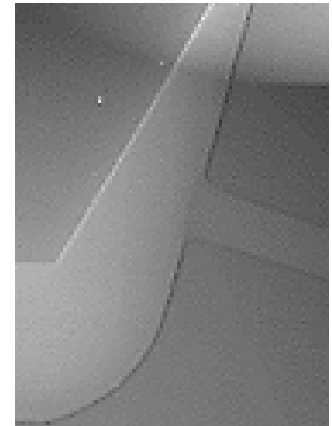
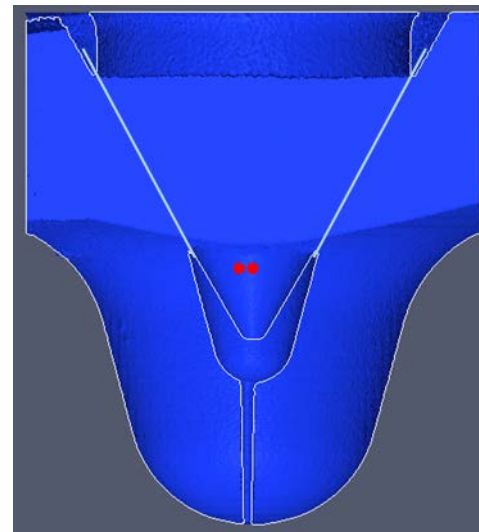
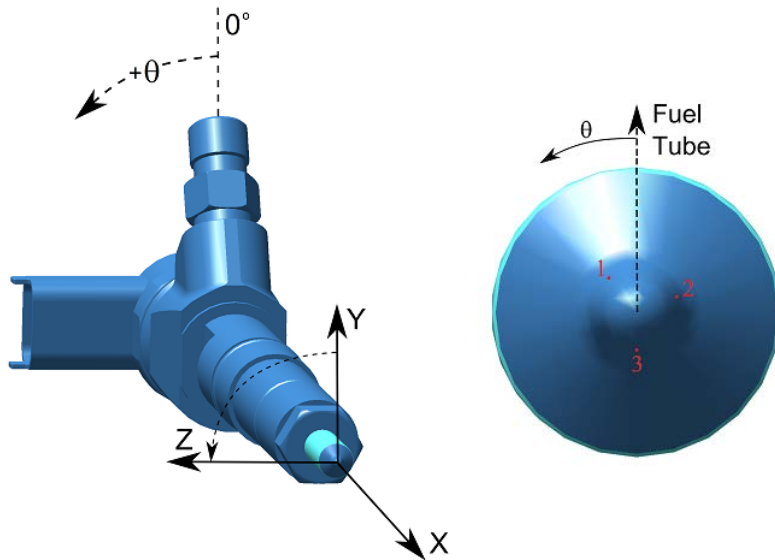
ECN Spray B nozzle

- Has the same size and KS specification as Spray A, but with a shorter length
- Side hole with $\psi = 72.5^\circ$ (145° full included angle)
- Plume 3, opposite the fuel tube, is the plume of interest

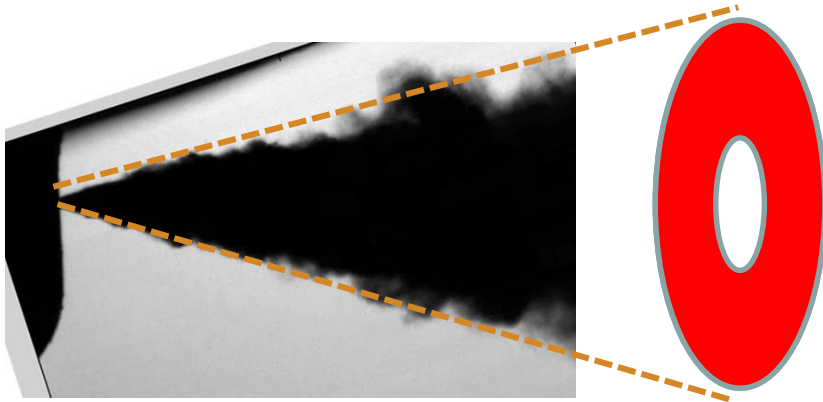
Spray B



Spray A



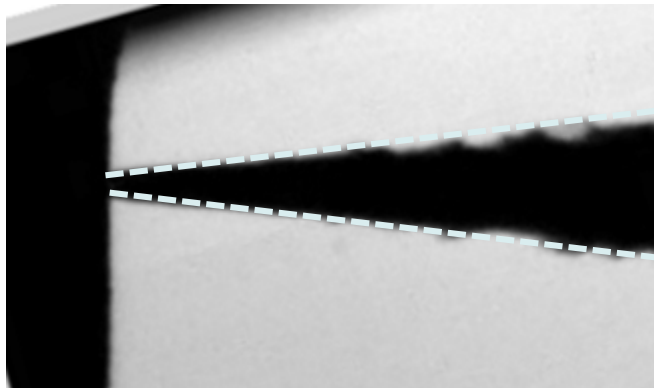
Lift-off length expected to increase in response to a narrowing of spreading angle



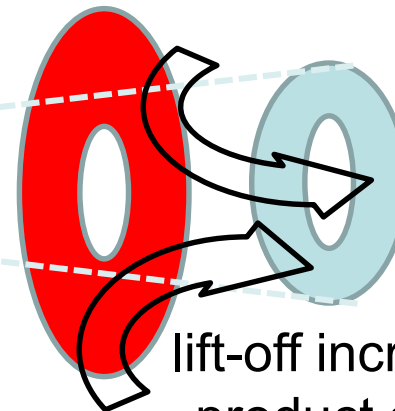
Ignition occurs → combustion product

Larger annulus of high-T products closer to the injector

At the timing of ignition



Narrowing the spreading angle



lift-off increases gradually as product gas is “consumed”

- Visualization confirms vapor and chemiluminescence ignition sites are at larger radius for Spray B compared to Spray A

Lift off length of Spray B compared to Spray A

